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Study on Flow Reattachment Length

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Abstract

The concept of eco-friendly trend of dam construction, Energy dissipation of hydraulic jump is a good type of energy dissipator. The use of stilling basin with step-down floor can remarkably decrease flow velocity on the floor and operation risk. In the context of a number of high dam adopted this energy dissipator in recent years, this article studied the relationship of reattachment length, step height, flow depth on the step and velocity on the step applying two-phase flow numerical simulation combining RNG $k-\varepsilon$ Turbulence mode with VOF method. The simulation result show that the reattachment length does not change with the velocity on step under certain conditions in the variable of Step height and flow depth on the step. Based on the dimensionless parameter of L/d (Reattachment Length /step height) and d/h_0 (step height/flow depth on the step), their fitting curves are established.

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Keywords: energy dissipation by hydraulic jump, Reattachment Length, Numerical Simulation, RNG $k-\varepsilon$ Turbulence model

1. Instruction

Flood discharge atomization in energy dissipation by hydraulic jump is very small, almost no impact on the surrounding environment. Under the concept of eco-friendly trend of dam construction, Energy dissipation of hydraulic jump is a good type of energy dissipater [1, 2]. Since 2000, a number of research institutions in China carried out a large number of studies for the hydraulics characters of the stilling basin with step-down floor. Model tests and numerical simulation results indicate that step-down significantly reduce flow velocity and pulsating pressure acting on the floor [3]. Table 1 lists some high dams that use stilling basin with sep-down floor. The height of these dams listed in table 1 is between 110m to 260m, the unit discharge on the step is between $100\text{m}^3 / (\text{s} \cdot \text{m})$ to $230\text{m}^3 / (\text{s} \cdot \text{m})$, the Froude

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number is between 5 to 12. So the stilling basin with step-down floor has wide range of applications. In this context, the problem of flow reattachment length in stilling basin with step-down floor was studied, by a large number of numerical simulation work.

Table 1 List of some large dams using stilling basin with tep-down floor

Project	Maximum of dam height/m	Inflow unite discharge / $\text{m}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$	Inflow Froude number Fr	Step height/m	country
Teri	260.5	109.6	12.5	3.5	India
Shushensk	245.0	183.7	10.7	4.3~6.0	Russia
Guandi	168.0	140.8	8.5	6.5	China
Xiangjiaba	161.0	225.3	6.4	9.0	China
Guanyinyan	159.0	159	5.9	7.5	China
myitsone	139.5	225	5.4	8.0	Myanmar
Tingzikou	110.0	133	7.0	8.0	China

The flow reattachment length downstream of the U_0 p-down is one of the important parameters to study other problems, for example, the vortex intensity, return flow velocity, angle between flow and floor and pressure gradient in the flow impact area. A sketch map of backward-facing flow pattern was given in figure 1. A strong shear and vortex flow structure is formed when the high velocity water flow through the step-down. The reattachment point was defined as the point that the turbulent diffusion flow contact stilling basin floor. Then the reattachment length L (figure 1) is defined as the distance from step-down to reattachment point.

In this paper, assume that the downstream water level is high enough, and in all conditions submerged jet flow can be formed. The problem was simplified two-dimension and studied by numerical simulation method.

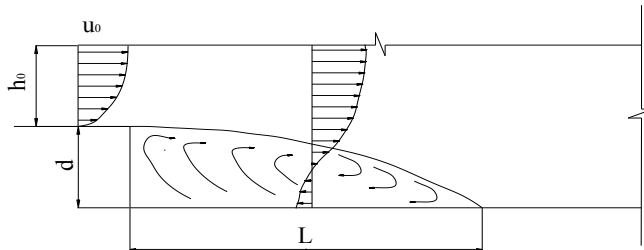


Fig.1 The sketch map of backward-facing step flow

2. Mathematical model

2.1. VOF model of water-air two-phase flow

In this study, the VOF method was used to track the interface. The basic idea is that, the function $\alpha_w(x, y, t)$ and $\alpha_a(x, y, t)$ respectively represent the volume fraction of water and air in computational field. At each discretized cell, a relationship was established as following,

$$\alpha_w + \alpha_a = 1 \quad (1)$$

The governing equation of water volume fraction is expressed as:

$$\frac{\partial \alpha_w}{\partial t} + u_i \frac{\partial \alpha_w}{\partial x_i} = 0 \quad (2)$$

where t is time; u_i and x_i are respectively velocity and coordinate components ($i=1, 2$). The interface between water and air was tracked by solving continuous equation (2).

Eq. (2) shows that the transient solver was used to advection field in VOF two-phase model according to unsteady flow process. Then by means of gradually iteration of time, the correct results for steady flow can be obtained.

2.2. Turbulent RNG k - ε model

The jet flow at step has the characteristics involving in high-speed turbulence and anisotropic [4, 5]. Thus, the RNG k - ε turbulent model was selected here. The governing equation was as following,

$$\text{Continuous equation: } \frac{\partial P}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \quad (3)$$

$$\text{Momentum equation: } \frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\left(\mu + \mu_t \right) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] \quad (4)$$

$$\text{k equation: } \frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[\left(\frac{\mu + \mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k - \rho \varepsilon \quad (5)$$

$$\varepsilon \text{ equation: } \frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[\left(\frac{\mu + \mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} G_k - C_{2\varepsilon}^* \rho \frac{\varepsilon^2}{k} \quad (6)$$

where ρ and μ are respectively the volume fraction average density and molecular viscous coefficient; u_i is velocity; P is corrected pressure; μ_t is turbulent viscous coefficient, and can be obtained by turbulent kinetic energy and turbulent dissipation rate, its expression is as,

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (7)$$

The G_k in Eq. (6) is turbulent kinetic energy production item induced by average velocity gradient, and can be expressed as,

$$G_k = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} \quad (8)$$

$$C_{2\varepsilon}^* = C_{2\varepsilon} + \frac{C_\mu \rho \eta^3 (1 - \eta/\eta_0)}{1 + \beta \eta^3} \quad (9)$$

where $\eta = S k / \varepsilon$, $S = \sqrt{2 S_{ij} S_{ij}}$.

Table 2 Constant in governing equation

C_μ	$C_{1\varepsilon}$	$C_{2\varepsilon}$	σ_k	σ_ε	η_0	β
0.0845	1.42	1.68	0.72	0.72	4.38	0.012

2.3. Numerical method and boundary condition

The computational filed was discretized by non-structured cell and control finite volume method. Then

differential equation was integrated at each control cell. A linearization was used to integral equation, and every variable were obtained.

Two-order upwind finite-volume method was used to volume fraction, momentum and diffusion term in turbulent kinetic energy closed equation; the couple of pressure and velocity was solved by PISO algorithm. The PISO is an algorithm in which corrected pressure and velocity represent a high approximated relationship, especially applicable to transient problems and can improve the convergence in highly distorted cell.

The computational field was simplified into two-dimensional plane. Inlet boundaries include water and vapor inlet boundaries. The former boundary condition was given the average velocity, and the latter boundary condition was given the pressure condition, its value is atmospheric pressure. The outlet boundaries were given related functions such as air and water, and latter function was the static pressure distribution. The solid boundaries were set as non-slip, and viscous layer was formulated by standard wall function. The initial boundary is filled with water.

3. Simulation result and analysis

Table 3 Result of numerical simulation

Example	Water depth /m	Step height/m	velocity /m · s ⁻¹	Reattachme nt length/m	Example	Water depth /m	Step height /m	velocity /m · s ⁻¹	Reattachme nt length/m
1	1	2	15	5.1	12	2	4	20	10.6
2	1	2	20	4.9	13	2	4	30	10.6
3	1	4	15	8.3	14	2	4	40	10.6
4	1	4	20	8.1	15	2	6	15	14.0
5	1	6	15	13.7	16	2	6	20	14.1
6	1	6	20	13.7	17	2	6	30	14.1
7	2	2	15	6.3	18	2	6	40	14.1
8	2	2	20	6.0	19	6	6	10	18.9
9	2	2	30	5.9	20	6	6	20	19.0
10	2	2	40	5.8	21	6	6	30	19.0
11	2	4	15	10.6	22	6	6	40	19.1

Table 4 Dimensionless result of numerical simulation

Example	Fr	$R_{se}=d/h_0$	$R_{td}=L/d$	Examp le	Fr	$R_{se}=d/h_0$	$R_{td}=L/d$
1	4.8	2.0	2.6	12	4.5	2.0	2.7
2	6.4	2.0	2.5	13	6.8	2.0	2.7
3	4.8	4.0	2.1	14	9.0	2.0	2.7
4	6.4	4.0	2.0	15	3.4	3.0	2.3
5	4.8	6.0	2.3	16	4.5	3.0	2.4
6	6.4	6.0	2.3	17	6.8	3.0	2.3
7	3.4	1.0	3.2	18	9.0	3.0	2.4
8	4.5	1.0	3.0	19	1.3	1.0	3.2
9	6.8	1.0	2.9	20	2.6	1.0	3.2
10	9.0	1.0	2.9	21	3.9	1.0	3.2
11	3.4	2.0	2.7	22	5.2	1.0	3.2

Twenty-two different examples were obtained by some factor combination involving in water depth

above step $h_0 = 1\text{m}, 2\text{m}, 6\text{m}$, step height $d = 2\text{m}, 4\text{m}, 6\text{m}$, and average flow velocity above step $U_0 = 10\text{m/s}, 15\text{m/s}, 20\text{m/s}, 30\text{m/s}, 40\text{m/s}$. The results were listed in Table 3. In order to find some regularity from lots of numerical results, simulation results were dimensionless based on step height d and averaged velocity above step U_0 . Expansion R_{se} was defined as the ratio of step height d and water depth above step h_0 . The ratio between reattachment L and step height d was marked as R_{Ld} . The dimensionless results listed in Table 4.

Simulated results in Table 3 were obtained under the hypothesis that the downstream flow was so enough deep that outflow from step becomes submerged jet flow. It can be seen that, as water depth known, reattachment length was proportional to step height. The higher the step height was, the longer the reattachment was (Fig. 2 shows the water flow field behind different height steps when water depth above step was 2m and average flow velocity was 20m/s). However, when step height and main water depth above step were known, the water flow velocity above step was hardly impact on the reattachment. Fig. 4 shows different flow fields behind step above different steps when water depth above step was 2m and step height was 4m .

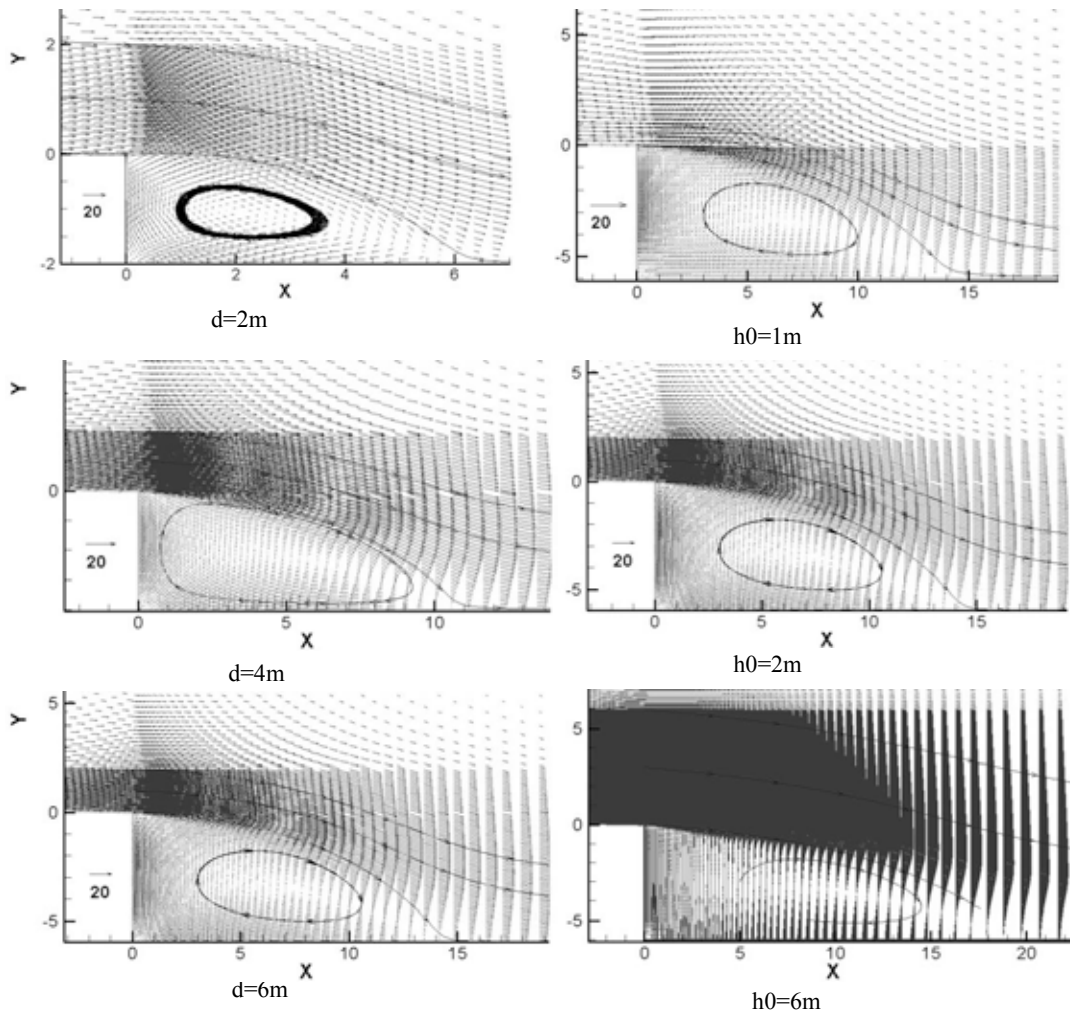


Fig.2 Flow distribution in different step height
When $h_0 = 2\text{m}$, $U_0 = 20\text{m/s}$

Fig.3 Flow distribution in different flow
depth When $d = 6\text{m}$, $U_0 = 20\text{m/s}$

As both of step height and water depth above step known, Reattachment Length is not change with velocity above step. The reason is that [6,7], (1) water flow behind step becomes a jet flow, and velocity gradient of jet boundary and relative stationary field increases, then results in increasing of shear stress; (2) from the condition of water flow under step, a closed area was formed by the bottom boundary of high-speed flow and facade of step as well as stilling basin bottom. Due to the high-speed water flow characteristic, a part of water was involved in high-speed main water which results in the forming of vortex flow structure. With increasing of velocity, velocity gradient of vortex flow structure increases which induces the pressure gradient increases and has an adsorption for main flow. Then two resistances were introduced. The superimposed force of these two resistances and increasing inertia induced by velocity increasing were canceled out each other, which results in a non-sense response of reattachment length to velocity change.

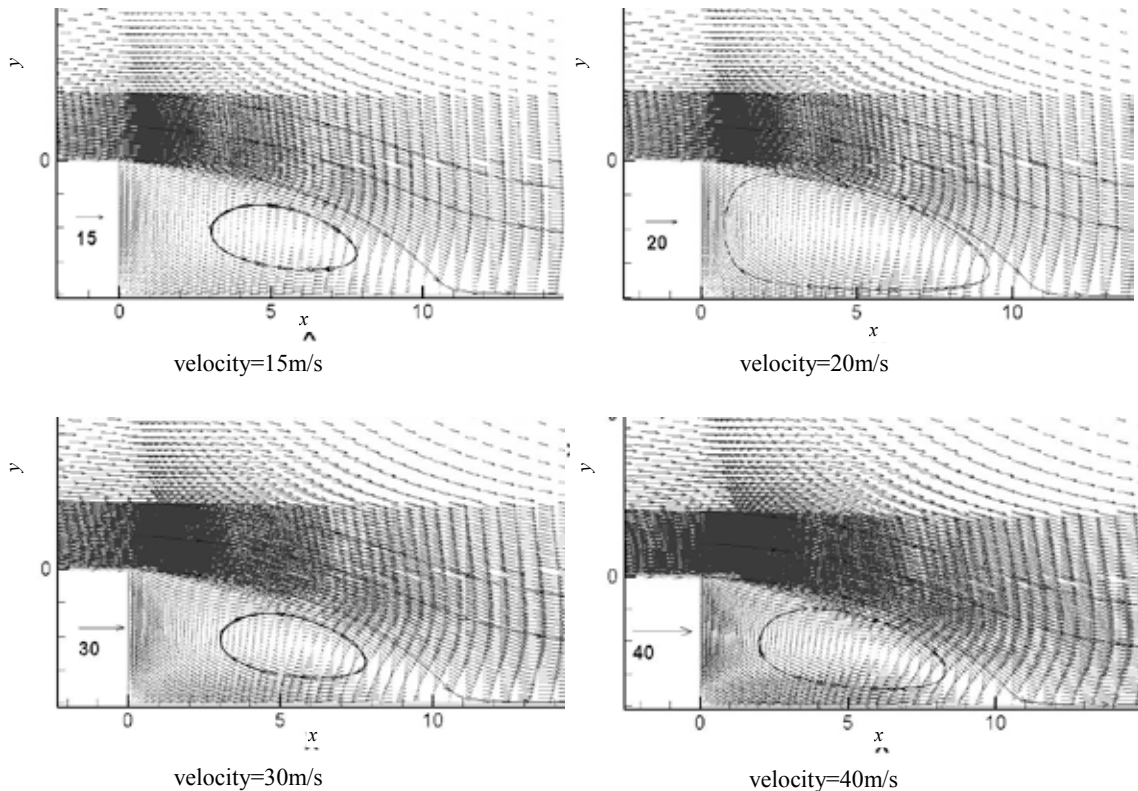


Fig.4 Flow distribution in different velocity when $h_0=2\text{m}$, $d=4\text{m}$

The dimensionless numerical results in Table 4 show that, the Frude number Fr above step is between 1.0 and 9.0, and the ratio value between reattachment length and step height is between 2 and 3. The value d/h_0 is between 1 and 2 where engineering situations were common, and values of L/d have some scatter degree, but the errors with average value of L/d were commonly smaller than 5%. Fig 5 was drawn according to the relationship between L/d and d/h_0 for all engineering situations. It can be seen from Fig.6 that all calculated points have clear distribution regularity. At the near of $d/h_0=4$, the value of L/d reaches the minimum. The well fitted curve by quadratic polynomial was given in Fig 5.

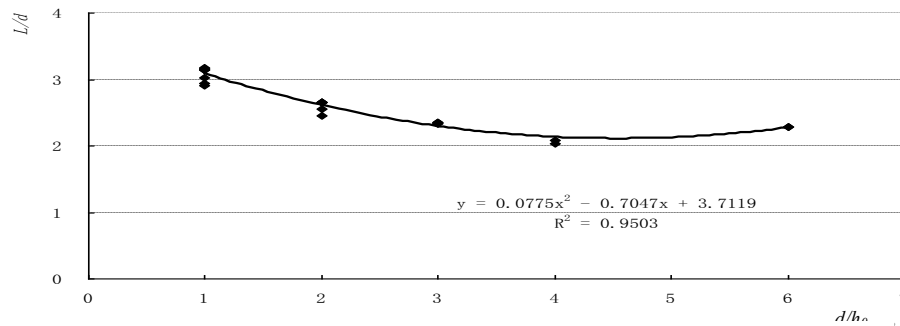


Fig.5 Relation between L/d and d/h_0

4. Conclusion

Under the trend of dam construction in the concept of eco-friendly, hydraulic dissipation has a distinct advantage. Setting step at front of stilling basin solves successfully a problem of high-speed at bottom harming engineering safety. Recently, many high dam project was set stilling basin with step-down floor. In the context, by use of two-phase flow numerical method combined with RNG k- ϵ turbulent model and VOF method, a study was carried out about the relationship among Reattachment Length, step height, water depth above step and velocity above step.

Numerical simulation results show that, under the condition of step height known, Reattachment Length is proportional to water depth above step. When water depth above step was known, Reattachment Length is proportional to step height. However, when step height and water depth above step were known, the velocity change of step was hardly impact the Reattachment Length.

Dimensionless of numerical simulation results shows that, a quadratic relationship between the ratio of Reattachment Length and step height L/d can be presented and ratio d/h_0 can be obtained. The ratio d/h_0 reaches minimum when $d/h_0=4$.

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